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Comparing greenhouse sprayers: the dose-transfer process†

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Abstract: Three sprayers were evaluated for their affect on retention and efficacy: a carbon dioxide powered high-volume sprayer, a DRAMM coldfogger, and an Electrostatic Spraying Systems (ESS) sprayer with air-assistance. The active ingredients used were spinosad and azadirachtin. The plant canopy was constructed in the greenhouse using potted soybeans (*Glycine max* (L) Merrill cr Pioneer 9392). Application efficacy with spinosad was assessed using thrips [Western flower thrips, *Frankliniella occidentalis* (Pergande)] and mite (two-spotted spider mite, *Tetranychus urticae* Koch) abundance on shoots and leaves. Application efficacy with azadirachtin was assessed using thrips and aphid (soybean aphid, *Aphis glycines* Matsumura) abundance on shoots and leaves. The atomization characteristics of each sprayer were measured using an Aerometrics phase/Doppler particle analyzer (PDPA) 100-1D. The results of four tests are presented. Two tests used each sprayer according to manufacturer recommendations. These are 'recommended volume' tests that confound differences in toxicant distribution caused by the sprayer with differences caused by changes in application volume. The other two tests were 'constant volume' tests in which all three sprayers were used to deliver the same application volume. Both types of test gave differences between sprayers in retention of toxicant, but only the recommended volume tests showed significant effects of the sprayers on pest abundance. We attribute this difference to the role played by changing application volumes in the dose-transfer process. The constant-volume tests showed that application equipment influences efficacy.

Keywords: spray application; retention; efficacy; *Glycine max*; *Frankliniella occidentalis*; *Aphis glycines*

1 INTRODUCTION

Pest-control application equipment should be evaluated based on our understanding of the dose-transfer process.[1] Optimal efficacy has been tied to spray droplet size,[2–5] and, in some cases, application equipment producing small droplets improves efficacy.[6–8] Toxicant concentration is also critical.[9,10] However, these aspects of toxicant delivery are not independent.[11] Dose (d) is the sum for all sizes (s) of the numbers of deposits of that size (n_s) and the toxicant per deposit (c_s).[1]

$$d = \sum_{s=0}^{s=\max} n_s c_s$$

A sprayer can influence efficacy only by changing droplet size, droplet density, droplet velocity, and in some cases droplet trajectory. Changing application volume also affects these factors and changes the physico-chemical characteristics of the liquid, thereby altering retention and diffusion rates. Experimental designs confounding application practices do not provide as clear a picture of the mechanisms involved.[12,13] Specific examples include: insect control in cotton,[14–16] chrysanthemums[17] and citrus;[18] herbicide efficacy;[19–22] and herbicide, fungicide and insecticide activity in cereals.[23,24]

Strategies for avoiding the confounding effects of equipment and changes in application volume have included: (1) standardizing volume median diameter (VMD) for different application volumes;[25,26] (2) standardizing the application for contact area;[27] and (3) comparing application equipment at a constant application volume.[28,29] These three strategies have some problems. Using a constant VMD is appropriate if VMD describes the important characteristics

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† Product and company names are necessary to report factually on methodology. However, the USDA and OSU neither guarantees nor warrants the standard of the product, and the use of the name by USDA or OSU implies no approval of the products to the exclusion of others that may also be suitable

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of the spray cloud as it pertains to retention and efficacy. No biological data are currently available to support this claim. Using a constant contact area requires some formula for converting VMD, NMD, or some other measure of atomization, into a contact area. Without this formula it will be difficult to relate these data to sprayer characteristics and difficult to use the data to design better application equipment. Furthermore, measuring contact area alone gives no measure of dispersion. Using a constant application volume probably evaluates all sprayers at different sub-optimal levels, and the poor performance of one sprayer may not be a fair evaluation of its potential. Simplicity is the advantage of using one application volume.

Another purpose of the current research is to demonstrate that toxicant distribution plays a significant role in pest management in the greenhouse environment. The importance of toxicant distribution has been shown in the laboratory,[11] but few greenhouse or field studies show the interaction between distribution and efficacy, although several authors have stated the effect.[30,31]

2 METHODS

2.1 Sprayer calibration and characterization

We used three sprayers: a DRAMM mini-coldfogger (DRAMM Corp, Manitowoc WI. model 600M, serial No 6M000101, 120 V 60 Hz) with the factory default nozzle (No 1304), an Electrostatic Spraying Systems (ESS; Watkinsville, GA) model EPS-5 with the MaxCharge nozzle, and a carbon dioxide powered hydraulic hand-held sprayer (equivalent to R&D Sprayers Inc, model HS) with a TXVS-6 (tests 1, 2) or TXVS-18 (tests 3, 4) hollow-cone nozzle (Spraying Systems Co, PO Box 7900, Wheaton, IL 60189-7900, USA, or www.TeeJet.com). We use the following abbreviations to refer to these sprayers: DRAMM, ESS, TXVS6, TXVS18.

The flow rate and ideal spray time are listed in Table 1. Sprayer flow rate was determined by placing 500 ml water in a beaker, submerging the nozzle, and spraying for 2 min, the process being replicated three times. For the ESS sprayer, the charging system and air assist were disconnected before measuring flow rate. There was no difference in flow rate with or without air assist. However, since the measurements without air assist were done the day before the tests, and flow rates with air assist were examined several weeks later, we present the former data.

Droplet cloud characteristics were measured using an Aerometrics PDPA 100 1D phase/Doppler particle measuring system using procedures described by Chapple and Hall,[32] but with the differences shown in Table 2. Measurements were taken 46 cm from the nozzle orifice with water that had been adjusted to 20 °C (temperature influences atomization).[33] The data presented are from three merged data sets having at least 10 000 counts each.

Table 1. Sprayer characteristics and settings

	DRAMM	ESS	Hydraulic
Recommended volume tests			
Nozzle	Factory default	Max-Charge®	TXVS-18
Pressure (KPa)	17 000	70	280
Flow rate (ml s^{-1})	12	3	21
ml applied	80	28	1738
Application Time (s)	7	10	80
Constant volume tests			
Nozzle	Factory default	Max-Charge®	TXVS-6
Flow rate (ml s^{-1})	12	3	6
ml applied	60	60	60
Application Time (s)	5	20	9

Table 2. PDPA-100 1D set-up parameters

	DRAMM and ESS	Hydraulic (TXVS-18)
Velocity (m s^{-1})		
Offset	15.00	7.00
Range	−0.95 to 54.96	−0.04 to 40.54
Minimum	0.0	0.0
Maximum	50.00	30.00
Refractive index	1.333	1.333
Diameter range (μm)	3.6 to 525.5	7.1 to 1041.2
Maximum diameter (μm)	300	700
Measurement range (μm)	8.6 to 300	20 to 700
Collimating lens (mm)	160	160
Transmitting lens (mm)	1000	1000
Receiver aperture (mm)	100	100
Collecting angle	r30	r30
Photomultiplier tube (PMT) voltage	350	350

2.2 Plant cultivation

Indeterminate soybeans (*Glycine max* (L) Merrill cultivar Pioneer 9392) were planted, one plant per pot, in March 2001 for tests 1 and 2. Plants were grown in a greenhouse set to heat if the temperature dropped below 18.3 °C in the daytime or 12.8 °C at night, and to activate cooling fans if the temperature exceeded 21.1 °C. Relative humidity was not controlled. Plants were fertilized twice per month with Peters 20-20-20 fertilizer, and watered as needed with tap water. When treated, plants were about 43 cm high, and old enough to have mature green bean pods, while a few plants had both green and dried pods. Prior to spraying, plants were moved into the treatment arena as described in Section 2.5.

Another group of soybeans (tests 3, 4) were planted December 2000. Plants were about 52 cm tall with pods at all stages of development at the time of treatment.

2.3 Efficacy test organism

Western flower thrips [*Frankliniella occidentalis* (Pergande)] populations were allowed to increase naturally on soybean plants. For test 1, thrips were abundant on all plants. For test 2, we infested soybean plants

with colony-reared soybean aphid (*Aphis glycines* Matsumura) two weeks prior to treatment. Infested leaves from colony plants were placed on leaves of the test soybean plants and removed 48 h later.

Pests occurring on soybeans for tests 3 and 4 were a result of a natural population present in the greenhouses and included thrips (western flower thrips and in test 4 mites (two-spotted spider mite, *Tetranychus urticae* Koch)).

2.4 Active Ingredient and tracer

The active used in test 1 was spinosad (228 g liter^{-1} SC; Spintor 2SC; Dow Agrosciences, 9330 Zionsville Rd, Indianapolis, IN 46268-1054). Tank mixes were prepared using Spintor + Rhodamine WT dye (Keystone Analine Corporation, 2501 West Fulton St, Chicago IL, 60612: lot A96L415) at 1.0 + 0.6 by volume. This mixture was applied at 0.837 ml liter^{-1} using the DRAMM, 2.408 ml liter^{-1} using the ESS, and 0.038 ml liter^{-1} using the TXVS-6.

The active ingredient used in test 2 was azadirachtin (45 g liter^{-1}EC; Neemix®4.5 provided courtesy of Certis Corp, 9145 Guilford Rd, Suite 175, Columbia, MD 21046. Lot NX003-1H). We used the same mixing procedure as described for test 1, and made a 1:1 substitution of the formulated spinosad to formulated azadirachtin.

The active ingredient used in test 3 was spinosad (116 g liter^{-1}SC; Conserve^{TM} SC, Dow Agrosciences, 9330 Zionsville Rd, Indianapolis, IN 46268-1054), at 2/3 of the label rate of 6 oz per 100 gallons. Our target application rate was 58.93 ml of a solution containing formulation at 1.73 ml liter^{-1} and Rhodamine at 2 ml liter^{-1}. Test 4 used 3.61 ml liter^{-1} Spintor 2SC, and Rhodamine was added at 3 ml liter^{-1}.

2.5 Plant canopy construction

Treatment plants were placed on two 0.98 × 2.42 m wooden tables 5 cm off the floor. Pots were arranged as depicted in Fig 1. The barrier plants provided barriers to spray movement. The plant canopy was sufficiently dense that one could not see soil, pots or table through the canopy.

2.6 Sprayer techniques

In all cases the goal was to apply the same dose through an imaginary window located 45 cm in front of row 1. The sprayer does the rest of the work to move the spray into the plant canopy. Plants were sprayed as shown in Fig 1. Plants sprayed with the ESS sprayer were treated from 2.4 m away, but the wand was about 0.6 m long. Plants were sprayed at a downward angle to treat the front and tops of plants. The nozzle was moved by hand during spraying with an up-and-down motion for the DRAMM and ESS sprayers and a circular motion with the hydraulic sprayer. Spraying in both tests was done between 0900 and 1400 h local time. In tests 1 and 2, all applications with the ESS were done first, followed by the DRAMM. In tests 3 and 4 we used the DRAMM sprayer first, then the ESS.

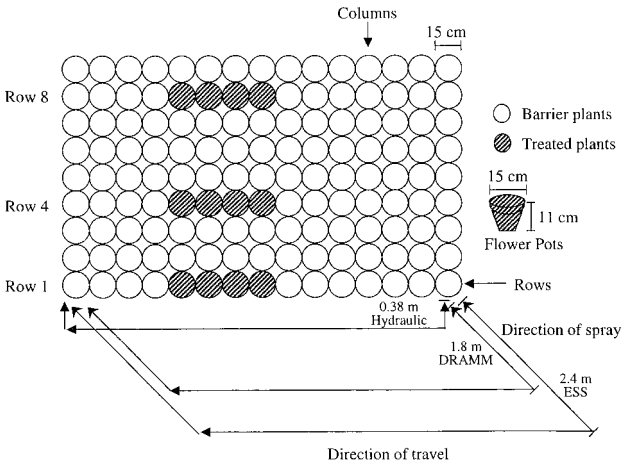

Figure 1. Treatment arena showing locations of sampled plants, direction of spray, distance from plants, and size of flower pots. Test 3 used plants from rows 1–5.

Plants were allowed to dry prior to being removed from the arena. This minimized spray redistribution. Plants for efficacy evaluation were moved to a separate bench, spaced such that they did not contact one another, and sampled 5 days post-treatment. After treatment, plants were watered directly into their pot to avoid removal of toxicant during the post-treatment interval.

2.7 Bioassay and tracer sampling

From each plant both leaves and shoots were sampled from several places within the canopy. Shoot is defined as new or young growth that may include any of the following: meristomatic tissue, flowers, flower buds, young pods <2.5 cm in length, and young leaves. Young leaves include those leaves where the individual trifoliate leaflets have not fully opened. For each plant, shoot 1 was always the furthest from the soil surface. Other shoots were taken with decreasing distance from the soil: five per plant in test 1, two per plant in test 2, and up to five in each of test 3 and 4. Shoots and leaves used for measuring retention were washed in a known volume of 95% ethanol to remove Rhodamine from the plant surface. We used a fluorometer (Turner fluorometer model 112, Sequoia-Turner Corp) to quantify the dye. Washed samples were placed in a drying oven at 40 °C until dry, and then weighed. Leaves and shoots for biological analysis were collected 5 days post-treatment using the same procedure as used for sampling plants for retention, and preserved in ethanol + water(75 + 25 by volume). After counting pests, samples were placed in a drying oven as previously described.

In test 1 we also sampled three leaflets per plant, using the central leaflet of the trifoliate leaf. In test 2 we sampled four leaflets per plant for spray retention and aphid abundance. In test 4 we sampled three leaflets per plant for spray retention and mite abundance. There was no attempt to distinguish between abaxial and adaxial leaflet surfaces. Leaves were not sampled for thrips in either test 3 or 4, and leaves were not

sampled for retention in test 3. Chronologically, tests 3 and 4 were the first tests and we were learning what we should sample.

2.8 Analysis

We analyzed the dye retention data using covariance models with tissue dry weight as the covariate, and sprayer, distance into canopy, and distance from the crown as categorical variables. We have reported type 1 sums of squares because the order in which variables enter the model is important. Insect counts are log transformed: mean and variance in insect counts are correlated by Taylor's power law $\log(s^2) = \log(a) + b\log(\overline{x})(r^2 = 0.94, P > F < 0.001, \log(a) = -3.376, b = 1.57), p = 1 - 0.5b = 0.215$, indicating that a log transformation is more appropriate.[34] To relate retention and efficacy we divided retention and pest counts by the dry weight of the sampled tissue and used pest per gram of tissue dry weight as the dependent variable. While a mean and variance for retention were correlated ($P > F < 0.001$), retention was not transformed. With log-transformed pest counts, the model for efficacy is log(abundance) = retention + distribution. If retention is log transformed then distribution will change efficacy exponentially while the effect of retention would be linear. These data do not support one model rather than the other.

We sprayed three canopies that differed from each other in the position of the leaves and stems of the plants comprising the canopy. Within each of these three canopies we sampled two columns of plants for retention and two for efficacy (Fig 1). The variability caused by different passes of the sprayer is of no real interest, and models included a blocking variable to account for this variability. Data were analyzed using SAS (SAS Institute Inc, SAS/STAT User's Guide, release 6.03, Cary, NC, 1988).

3 RESULTS

3.1 Sprayer output

Droplet size, number and velocity influence both retention and efficacy. However, no biological data exist that show what measures are important. We describe the sprayers using standard measures (Table 3), with the realization that other measures exist and may prove more useful. Lefebvre[35] defines these and other ways to evaluate atomization characteristics.

3.2 Overview

Plants treated with the DRAMM sprayer at recommended volumes retained more material than plants treated with the ESS sprayer, although the difference was only significant in test 1 (Table 4). Plants treated with the hydraulic sprayer at recommended volumes retained significantly more dye than the other treatments in test 1, but not in test 2. Treatments with the hydraulic sprayer at constant volume resulted in higher retention, followed by the DRAMM sprayer and finally the ESS sprayer. However, there was no easily observable relationship between higher retention and fewer pests, nor was there a consistent ranking of the sprayers based on efficacy.

We do not know why dye retention in test 2 was high relative to all other tests. Mite abundance was higher in sprayed treatments. The label rate for mite control is higher than for thrips control, and we used a rate suitable for thrips control. Moreover, thrips prey on mites. An ineffective application along with removing natural enemies may account for the observed effect.

3.3 Retention of dye

Sprayer type at recommended or constant volume was significant, as was distance from the sprayer (Table 5). There was also a significant interaction between sprayer and distance. This occurs because sprayers

Table 3. Sprayer characterization using the PDPA-100 1D

	VMD[a] (μm)	NMD[b] (μm)	Droplet size specific velocity (m s^{-1}) 50 μm	100 μm	300 μm	Relative span
ESS	34.2	20.1	16.5	25.8	na	1.25
DRAMM	41.0	29.2	16.5	20.1	na	0.79
TXVS-6	147.0	34.2	2.6	1.7	4.4	1.42
TXVS-18	254.0	31.0	2.8	2.1	5.6	1.26

[a] Volume median diameter.
[b] Number median diameter.

Table 4. Average pest abundance and average retention of dye by greenhouse grown soybean

Treatment	Thrips (g^{-1})	Aphids (g^{-1})	Mites (g^{-1})	Dye (μg g^{-1})
Test 1				
DRAMM	150 a			20 b
ESS	240 a			10 c
Hydraulic	200 a			30 a
Untreated	370			
Test 2				
DRAMM	50 ab	330 a		150 a
ESS	100 a	170 b		120 a
Hydraulic	30 b	140 b		90 a
Untreated	20	610		
Test 3				
DRAMM	50 bc			30 a
ESS	40 c			20 a
Hydraulic	60 b			30 a
Untreated	190 a			
Test 4				
DRAMM	30 b		1220 a	23 ab
ESS	20 b		710 b	16 b
Hydraulic	50 a		770 b	40 a
Untreated	50 a		510 b	

Numbers in a column with the same letter are not significantly different by LSD test, 0.05 level. All models are significant $P > F < 0.001$ except retention model for test 2($P > F = 0.34$), retention model for test 3($P > F = 0.08$), and retention model for test 4($P > F = 0.04$).

Table 5. ANCOVA models predicting micrograms of dye recovered

	Shoots				Leaves		
	Recommended volume		Constant volume		Recommended volume		Constant volume
	Test 1	Test 2	Test 3	Test 4	Test 1	Test 2	Test 4
Model $P > F_2$	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Adjusted R^2	0.44	0.40	0.61	0.62	0.72	0.58	0.58
Source	$P > F$[a]	$P > F$	$P > F$	$P > F$	$P > F$	$P > F$	$P > F$
Dry weight			<0.001	<0.001	0.028		
Block							
Sprayer	<0.001	0.003		0.001	<0.001	0.014	<0.001
Row	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Row * Sprayer	<0.001		0.012	<0.001	<0.001	<0.001	<0.001
Location	<0.001				<0.001	<0.001	
Sprayer * Location			0.027		0.016	0.033	
Row * Location			<0.001	0.041			
Row * Location * Sprayer					0.031		

[a] $P > F$ values are based on type 1 sums of squares, and values >0.05 are not shown.

Table 6. ANCOVA models predicting pest abundance on shoots and leaves[a]

	Thrips RV[b] shoots test 1	CV[b] shoots test 3	CV shoots test 4	Aphids RV shoots test 2	Mites CV shoots test 4
Model $P > F$	<0.001	<0.001	0.012	0.033	<0.001
Adjusted R^2	0.34	0.43	0.26	0.29	0.36
Source	$P > F$[c]	$P > F$	$P > F$	$P > F$	$P > F$
Retention		0.006	<0.001		<0.001
Block	0.045			0.019	
Sprayer	0.005	0.012	0.025		<0.001
Row		<0.001	0.004	0.015	
Row * Sprayer					
Location	<0.001				0.003
Sprayer * Location	0.004			0.029	0.001
Row * Location					
Row * Location * Sprayer					

[a] The five models not shown were not significant: aphids and mites on leaves, thrips on leaves test 1 and 2, and thrips on shoots test 2.
[b] RV = recommended volume, CV = constant volume.
[c] $P > F$ values are based on type 1 sums of squares, and values >0.05 are not shown.

produce characteristic droplet spectra (Table 3), and friction with the atmosphere, evaporative losses and collisions with surfaces change the droplet cloud in ways that depend on the droplet spectrum, and alter the droplet spectrum.[12]

3.4 Efficacy

If, on average, leaves in the same position in the canopy behave similarly regarding spray retention, the dye should be an accurate estimator of toxicant retention. Correlating pest abundance to retention also requires a common basis for comparison. We achieve this by converting all numbers to a 'per gram tissue dry weight' basis.

Sprayer type at recommended volume was a significant predictor of pest abundance in one out of six models examined, but sprayer type at constant volume was significant in three of the four models examined (Table 6). The estimated dose was not significant in any of the models for recommended volume, and three out of four models at constant volume.

4 DISCUSSION

Toxicant distribution plays a role that may be more important than quantity—at least within the range encountered in these tests. In Table 6, the variability explained by retention is less than that explained by the other variables (based on type 1 sums of squares). Thus, measuring retention is important in designing experiments to evaluate sprayer efficacy, but measuring retention alone is meaningless without accompanying biological data.

What is more interesting is the role of the sprayer in tests 3 and 4 summarized in Table 6. Given that we have corrected the models for differences in dose (as measured by retention), we find that sprayer type explains a significant proportion of the remaining variability. This could only happen if atomization

differences play a role in efficacy, and the only way that is possible is if toxicant distribution plays a significant role in determining the biological effect of a toxicant. The significant effects of distance from sprayer (row) and location on the plant are also attributable to changes in toxicant distribution caused by changes in the droplet cloud impacting the plant at these locations.

Despite the similarity between our comparisons of sprayers at recommended and constant volumes, the interpretation of the results from constant-volume tests is more direct. Using a recommended volume test to compare sprayer performance may be valid if it is demonstrated that each sprayer was used optimally. Currently, no such data are available for any sprayer. The good performance of the hydraulic sprayer suggests that we do not fully understand even this 'well-known' application device.

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